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HIGH-ENERGY SOLAR PHENOMENA—A NEW ERA OF SPACECRAFT MEASUREMENTS

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A CORRELATION BETWEEN 4-8 MEV GAMMA-RAY-LINE FLUENCE AND >50 KEV X-RAY FLUENCE IN LARGE SOLAR FLARES

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ABSTRACT

For large flares observed by the Solar Maximum Mission (SMM) satellite from 1980-1982, we find a reasonably good correlation between 4-8 MeV gamma-ray-line (GRL) fluences and >50 keV hard X-ray fluences. We find no compelling evidence for a distinct population of large hard X-ray flares that lack commensurate GRL emission. Our results are consistent with the acceleration of the bulk of the ~100 keV electrons and ~10 MeV protons (i.e., the populations of these species that interact in the solar atmosphere to produce hard X-ray and GRL emissions) by a common process in large flares of both long and short durations.

INTRODUCTION

Forrest[1] found that the >300 keV electron bremsstrahlung continuum and 4-8 MeV GRL emissions of solar flares were correlated down to the GRL detection threshold of the Gamma Ray Spectrometer[2] (GRS) on SMM. Thus Forrest[1] and Chupp[3] argued that all flares with >300 keV continuum could be GRL flares, given a sensitive enough detector. Bai[4] criticized this inference because, in his picture, protons and the bulk of relativistic electrons are both accelerated by a second-step process that operates only in GRL flares. From Bai's viewpoint, the correlation found by Forrest[1] was not surprising but was instead an expected result of second-step acceleration. Bai[4] argued that there exists a population of large hard (e.g., >50 keV) X-ray flares with steep spectra ("non-GRL flares" that result from a primary or "first-step" acceleration mechanism) in which a second-step process does not operate to accelerate particles to high energies. Such events should weaken any correlation in a plot of >50 keV emission vs. 4-8 MeV line emission for a sample of large flares.

To test Bai's[4] contention, we compared flare 4-8 MeV GRL fluences with >50 keV fluences to see if the correlation reported by Forrest[1] could be extended to lower X-ray energies. To conduct this test, we made use of data reduction/analysis programs recently completed by the Hard X-ray Burst Spectrometer (HXRBS) team that enables one to readily determine X-ray fluences. The ratio of the flare bremsstrahlung continuum emission produced by accelerated electrons to the GRL emission produced by protons provides a measure of the electron to proton (e:p) ratio of interacting particles. Cane, McGuire, and von Rosenvinge[5] were the first to show that the e:p ratios of solar energetic particle (SEP) events observed in space following flares are ordered by the flare duration, with impulsive flares having higher e:p ratios. Thus we also examined the effect of flare duration on the e:p ratio of the particles that interact at the sun to produce X-ray and GRL emission to see if a similar relationship held.

The analysis is described in Section 2; results are discussed in Section 3.

ANALYSIS

Fluence Calculation. The HXRBS detector[6] consists of a CsI(Na) scintillation spectrometer with a large anticoincidence shield. The HXRBS Event Catalog[7] contains 7045 events for the three years 1980-1982. As the first step in our procedure for obtaining fluences, we required that an event have a detectable flux in Channel 3 as reported in the HXRBS Catalog. From February 1980 - December 1982, the low energy cut-off for this channel increased from 49 keV to 63 keV. Of the events with a signal in Channel 3, we selected those having durations >200 s and/or peak count rates, integrated over all channels, of >100 c s^{-1}. Non-solar events and events flagged as having "noisy data" were not considered. Each selected HXRBS event was broken down into discrete time intervals by the automated procedure described in Crosby, Aschwanden, and Dennis[8]. Then the integral count rate above pre-event background for each interval was deconvolved to approximate the incident photon flux, which was assumed to have a power-law spectrum of the form $E^{-\gamma}$, using conversion factors generated by modeling the detector response to an incident flux with such a spectrum. A least-squares spectral fit for each interval was performed using an automated procedure, and the fit parameters were stored in a "summary file". There were 2878 such events during 1980-1982. Only flare intervals with power-law slopes greater than 1.1 or less than 7.0 were used in the fluence calculations. For γ < 1.1, the integral of the X-ray spectrum diverges, while values of γ > 7.0 may reflect a thermal spectrum and are, in any case, unreliable because of the relatively poor energy resolution of the CsI(Na) detector. To ensure that we considered only detected >50 keV emission and were not merely integrating background noise from erroneous spectral fits both early and late in flares when the counting rate is low, we followed the procedure of Crosby, Aschwanden, and Dennis[8] and only considered those intervals for which the calculated value of the thick-target energy in >50 keV electrons exceeded the value of this parameter averaged over all intervals that met the above criteria. The >50 keV fluence value for a given event was then obtained by summing the contributions from all valid intervals.

As a check on the accuracy of the HXRBS fluences obtained by the above method, we compared our >50 keV fluences with preliminary 40-140 keV fluences measured by the GRS on SMM (Vestrand, private communication, 1992) for a sample of large flares observed from 1980-1982. The result of the HXRBS-GRS comparison is shown in Figure 1. The plot contains nearly all HXRBS events with >50 keV fluences ≥5000 photons cm^{-2} for which the peak of the burst was observed, and a decreasing fraction of such well-observed events for smaller fluences.

The circled data points in Figure 1 indicate events affected by pulse pile-up[9]. The presence of pulse pile-up in an event is revealed by a comparison of the outputs from the two X-ray detectors on GRS. One of these detectors has an additional iron filter to block lower energy photons and, therefore, is less susceptible to pulse pile-up distortion of counting rates. Any difference in the output of the two detectors for a common energy range can be attributed to a greater degree of pulse pile-up in the detector without this filter. In terms of their level of "shielding", the two GRS X-ray detectors bracket the HXRBS X-ray detector, one being more heavily shielded and one less so. Thus an indication of pile-up in the GRS X-ray detectors indicates that the output from the HXRBS detector may also be affected, especially because the HXRBS detector is larger than the GRS detectors. The fact that the circled data points in Figure 1 generally lie above the least-squares fit line is consistent with the relative susceptibilities of the HXRBS and GRS detectors to pulse pile-up. The cause of the discrepancy between GRS and HXRBS fluences for the two data points flagged with question marks remains to be determined.

As shown in Figure 1, there is good agreement between the two fluence measures, especially when the circled data points are ignored. The dashed line in Figure 1 is the least squares fit to the "good" data points (not circled or flagged with a "?"); it can be used to correct HXRBS fluences for pulse pile-up affected events for which the GRS 40-140 keV fluence

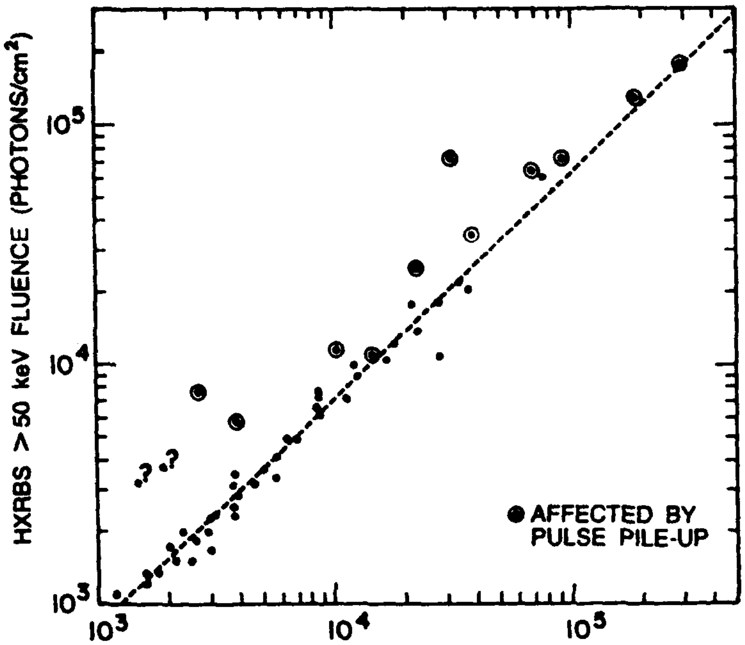

Fig. 1. Plot of HXRBS >50 keV fluence vs. GRS 40-140 keV fluence for large flares.

(from the more heavily shielded detector) has been determined. The assumption underlying any such correction is that the GRS X-ray detector with the additional filter is not affected by pulse pile-up. This assumption may not be valid for intense events, particularly those with a soft spectrum, and for such events the corrected >50 keV fluence will only be an upper limit. We note that the ratio of the GRS fluences to the SMM fluences from the dashed-line fit is ~1.6, corresponding to a power-law energy spectrum with an exponent of ~ -3.2 (cf., ref. 10). Such a flat spectrum results, at least in part, from the tendency of big flares to have harder spectra[11].

<u>4-8 MeV Fluence vs. >50 keV Fluence</u>. Figure 2 is a plot of 4-8 MeV fluence vs. >50 keV fluence (corrected for pulse pile-up as necessary and when possible) for all HXRBS summary file events occurring from 1980-1982 with >50 keV fluences ≥500 photons cm^{-2}. The 4-8 MeV fluences were taken from Cliver et al.[12] The "x" data points in this figure are for non-GRL flares; the values of the ordinates for these points correspond to a 4-8 MeV fluence upper limit of ~0.5 photon cm^{-2} (plotted between 0.35 - 0.9 photon cm^{-2} because of space limitations), the nominal detection threshold of the GRS for GRL emission. The data points with horizontal lines drawn through them indicate that a correction for pulse pile-up (using Figure 1) has been applied to the >50 keV fluence. A relationship similar to that depicted in Figure 2 has been found to exist between the GRS 40-140 keV fluence and the 2.2 MeV neutron capture line fluence[13]. Figure 3 shows an updated version (from Vestrand[14]) of the correlation obtained by Forrest[1] between the >300 keV fluence and the 4-8 MeV fluence for all flares with >300 keV emission observed by GRS during 1980-1985. The plots in Figures 2 and 3 are similar in appearance. In both cases the scatter increases for lower energies, although to a greater degree in Figure 2. There is no "population" of large >50 keV fluence events that lack detectable GRL emission in Figure 2. There are two outliers, labelled with their dates, that fall below the general trend of the data. One of these was an event on 1982 July 12 event that lacked detectable GRL emission; the other outlier occurred on 1981 October 7. For both of the outlying events pulse pile-up effects were severe, particularly so for 1982 July 12. For that

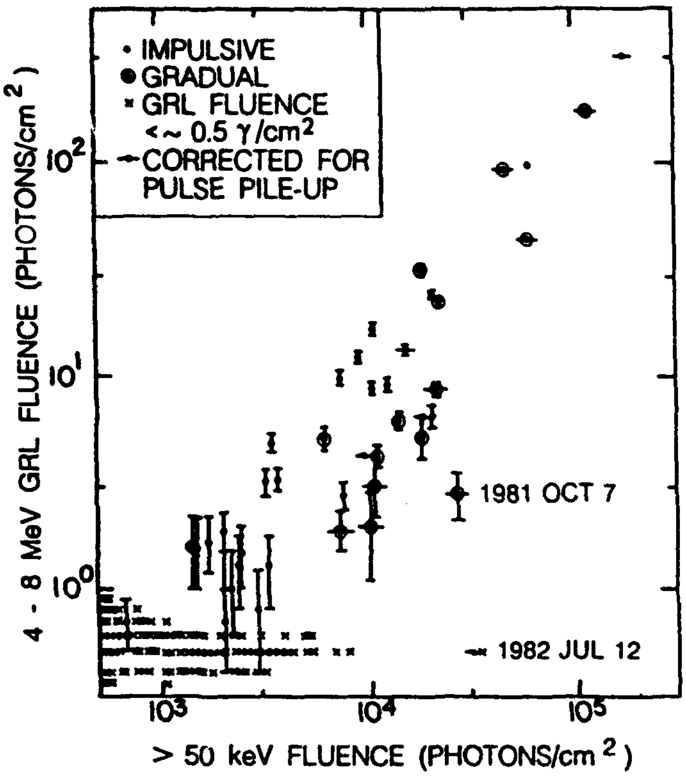

Fig. 2. Plot of GRS 4-8 MeV GRL fluence vs. HXRBS >50 keV fluence, 1980-1982.

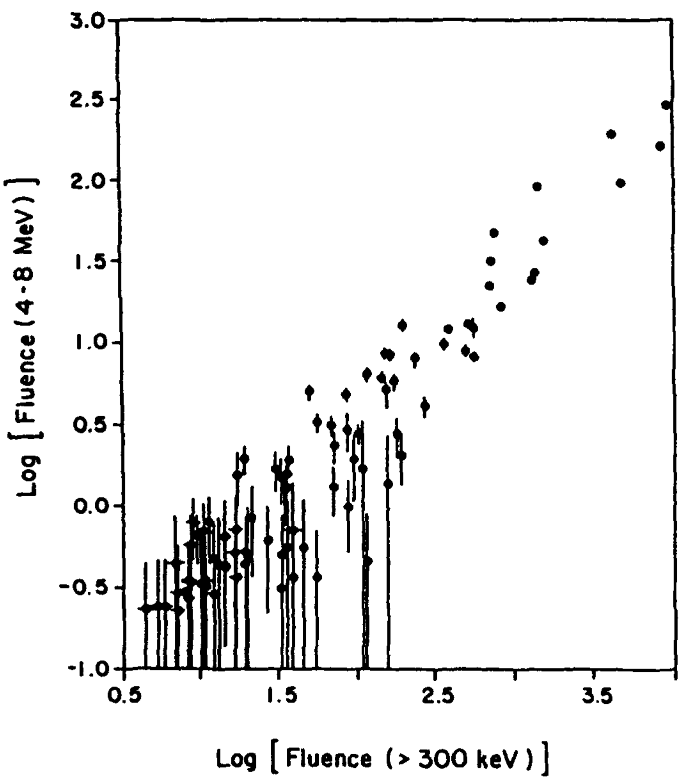

Fig. 3. Plot of 4-8 MeV excess vs. >300 keV electron bremsstrahlung continuum fluence for flares observed by the GRS, 1980-1985 (from Vestrand[14]).

event, the 40-140 keV profile from GRS was so distorted that any fluence value obtained would have been meaningless (Vestrand, private communication, 1993). A leftward pointing arrow on the data point for the July 12 event indicates that the plotted value is an upper limit. Such arrows are also used for two other piled-up events for which the 40-140 keV fluence was not determined. As noted in Section 2.1, however, even the data points corrected for pulse pile-up represent, in a sense, upper limits because the 40-140 keV fluence obtained from the more heavily shielded X-ray detector on GRS that is used to obtain a corrected >50 keV fluence via Figure 1 may also be distorted by pulse pile-up. The circled data points in Figure 2 represent long duration flares following the classification scheme of Cliver et al.[12] (cf., refs. 4, 5). As can be seen in the figure, there is a tendency for these events to have higher e:p (i.e., >50 keV bremsstrahlung fluence : 4-8 MeV GRL fluence) ratios than do the impulsive flares; their data points tend to lie to the right of the trend line, thereby increasing the scatter. (The large (>3000 photons cm^{-2}) non-GRL flares, indicated by "x" data points, are also characteristically gradual events.) The difference in e:p ratios between the gradual and impulsive flares is not great, about a factor of two in the medians, and may be due to the relative sensitivities of the HXRBS and GRS detectors late in long duration events when GRL fluxes fall below the detection threshold. For comparison, Kallenrode, Cliver, and Wibberenz[15] found a difference of a factor of $\lesssim 10$ between the average e:p ratios of SEPs from gradual and impulsive flares. For SEP events, however, the difference is in the opposite direction with higher e:p ratios observed in SEP events associated with impulsive flares. The small, possibly instrumental, difference that we find between e:p ratios of interacting particles from gradual and impulsive flares is consistent, to first order, with the recent result of Ramaty et al.[16] who showed that the ratio of the numbers of interacting 0.5 MeV electrons to 10 MeV protons is independent of flare duration.

There is evidence for a class of impulsive γ-ray flares, called electron-dominated events[17], in which line emission is missing or muted. While such events might be representatives of the population of large "first-step" non-GRL flares argued for by Bai (1986) in the two-step scenario, an identification of the two groups is problematical because the bremsstrahlung continuum in electron-dominated events extends beyond 10 MeV (up to 60 MeV in certain cases) and the spectra exhibit a tendency to flatten with increasing energy. There were eight such flares in the total sample, 1980-1989, of GRS flares that were intense enough to be spectrally analyzed[17]. Three of these flares were observed during the 1980-1982 period we considered (Rieger, private communication, 1990): 1980 June 4, 1980 June 29, and 1982 June 15. Each of these flares had >50 keV fluence in the range from 2-4 x 10^3 photons cm^{-2}; thus, their data points lie in the lower left-hand side of Figure 2 where the scatter is greatest. Because of the subtraction technique used to determine the nuclear excess[14], the line emission in these events is over-estimated[18]. However, even if we reduce the GRL emission observed in these events from the deduced values of ~ 2-5 photons cm^{-2} to the GRS instrumental background of ~0.5 photons cm^{-2}, the altered data points remain within the scatter and our basic result - the apparent correlation of >50 keV and 4-8 MeV fluences for large flares observed from 1980-1982 - is not changed.

DISCUSSION

The correlation in Figure 2 that we find between >50 keV fluences and 4-8 MeV GRL fluences suggests that the bulk of ~100 keV electrons and ~10 MeV ions (needed to produce >50 keV continuum and 4-8 MeV GRLs, respectively) are accelerated in a common acceleration process in large flares (cf., refs. 19, 20). This would be the simplest explanation for the correlation. We note, in particular, the absence of a well-defined population of flares with large >50 keV fluences but without detectable GRLs. In the picture of Bai[4], such events would be those in which the second-step process was not operating. The two high fluence events that are deficient in GRL emission (1981 October 7 and 1982 July 12) have

characteristics (delay of high energy X-rays, at least for 1981 October 7, and type II association) that Bai and Dennis[21] and Bai[4] reported for "normal" GRL flares. The anomalous position of the 1982 Jul 12 event is presumed to result primarily from pulse pile-up in the HXRBS detector. In addition, both the 1982 Jul 12 and 1981 Oct 7 events were gradual flares and there is a tendency in Figure 2, that may be an instrumental effect, for gradual events to have larger e:p ratios than impulsive events. We note that gradual events, in general, contribute much of the scatter in the correlation plot in Figure 2. Again, while these events appear to be, as a group, slightly deficient in GRL emission, they exhibit spectral delays and are highly associated with type II emission. Thus there is little evidence that they constitute a separate "class" of event. The common acceleration process we propose for ~100 keV electrons and ~10 MeV ions in large flares could still be a second-step process, following an initial injection as envisioned by Bai[4] (cf., refs. 22, 23), but such a second-step process must dominate electron acceleration down to energies $\lesssim$100 keV rather than the >200 keV level suggested by Bai[4].

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